pletely analogous to the one just discussed in connection with SU(3) since the nonrenormalization theorem also applies to SU(2). Regarding the validity of first-order perturbation-theory calculations with a chiral Lagrangian we feel that the results obtained in Ref. 11 show that is is perfectly legitimate. The author wishes to thank A. Zepeda for bringing this problem to his attention.

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Polarization of Λ's and $\bar{\Lambda}$'s Produced by 400-GeV Protons

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We have measured the polarization of 3×10^6 Λ^0 and 2.5×10^5 $\bar{\Lambda}^0$ hyperons produced by 400-GeV protons on a beryllium target. The hyperons were detected at a fixed angle of 7.2 mrad and in the momentum range from 50 to 300 GeV/c for Λ^0 and 50 to 200 GeV/c for $\bar{\Lambda}^0$. The Λ^0 polarization agrees with that measured at 24 and 300 GeV and is -0.24 ± 0.04 at $p_T=2.1$ GeV/c. The $\bar{\Lambda}^0$ polarization is zero up to $p_T=1.2$ GeV/c.

The discovery[1] that Λ^0 hyperons are polarized when produced by the interaction of 300-GeV unpolarized protons with an unpolarized target implies, contrary to early expectations, that spin effects are important in high-energy particle production. Where measured, the polarization has the following properties[1-3]: (i) The polarization direction is perpendicular to the production plane as required by parity conservation. (ii) The magnitude increases monotonically with transverse momentum from 0 at $p_T=0$ to over 20% at $p_T=1.6$ GeV/c. (iii) The polarization does not depend strongly on the longitudinal momentum of the produced Λ^0 for Feynman $x = 2p_L^{\text{c.m.}}/\sqrt{s}$ between $0.2 < x < 0.8$. (iv) No significant difference is observed in the polarization from beryllium, copper, and platinum targets. (v) The p_T dependence of the polarization for an incident proton energy of 300 GeV is consistent with that for 24 GeV.

A polarization measurement is a more delicate diagnostic of reaction dynamics than is a cross section. Polarization requires coherence between at least two amplitudes, and therefore is sensitive to small spin-dependent terms. The existence of substantial polarization in an inclusive reaction suggests that only a few amplitudes contribute to the production process. One model which might satisfy this requirement of simplicity is the quark model. Within this model hadron interactions are described in terms of the elementary interactions of constituent quarks. This description is presumed to become more relevant as the transverse momentum involved in the reaction increases. The simplest version involving spin is the SU(6) quark model. It builds the Λ^0 hyperon of u, d, and s valence quarks, while the $\overline{\Lambda}^0$ is composed of $\bar{u}$, $\bar{d}$, and $\bar{s}$ quarks. In each case the nonstrange quarks form a singlet spin state so that the spin of the hyperon is the spin of a single quark, the strange quark. No other hadron has this property.

The present experiment extends the measurement of P_Λ, the polarization of Λ^0 hyperons produced by protons interacting in a beryllium target, to a projectile energy of 400 GeV and a transverse momentum of 2.1 GeV/c. In addition this is the first experiment to measure the polarization of $\overline{\Lambda}^0$ hyperons with sufficient accuracy to make a meaningful comparison between P_Λ and $P_{\overline{\Lambda}}$. The two polarization measurements give a comparison between quite different production mechanisms. For forward production, $x > 0.2$, the Λ^0's are presumably fragments of the incident proton whereas the $\overline{\Lambda}^0$'s seem to be the result of baryon pair production from the central region.[3,4] If the SU(6) quark model applies, and if $(s\bar{s})$ pairs are always produced polarized in hadronic collisions, the $\overline{\Lambda}^0$'s might be polarized as well as the Λ^0's.

The measurements were performed with the Fermilab neutral hyperon beam and spectrometer described previously.[1,3,4] The apparatus is shown in Fig. 1. A 400-GeV proton beam was deflected in the vertical plane onto a 28.3-g/cm^2 Be target, T, to give a production angle of 7.2 mrad between the incident proton beam and the collimator axis defining the neutral beam. The collimator axis ($+z$ downstream), the vertical magnetic field in the collimator ($+y$ upwards), and the horizontal ($\hat{x}$) formed the right-handed orthogonal coordinate system ($\hat{x}, \hat{y}, \hat{z}$) shown in Fig. 1. The incident proton beam was in the y-z plane and could be brought onto the target from below, +7.2 mrad, or from above, −7.2 mrad. The polarization vector was parallel to the unit vector $-\hat{n} = -(\vec{k}_p \times \vec{k}_\Lambda)/|\vec{k}_p \times \vec{k}_\Lambda|$, so that positive and negative production angles gave equal but opposite polarizations in space. This allowed the elimination of biases in the measurement. Because of the small size of the collimator aperture, the deviation of the Λ^0 direction from $\hat{z}$ was always less than $\frac{1}{2}$ mrad.

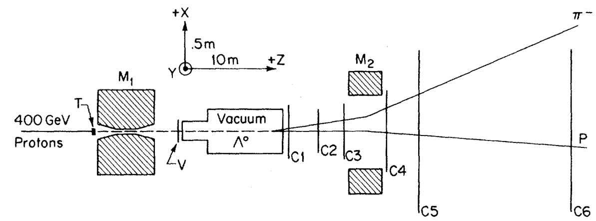

FIG. 1. Plan view of the neutral hyperon beam and spectrometer. The production angle was in the y-z plane and is not shown in this view. The elements are described in the text. The electronic trigger required no signal from the veto counter, V, and one hit in each chamber, C_i, except C_5 in which two hits one on each side of the neutral beamline were required. A typical $\Lambda^0 \to p\pi^-$ decay is shown.

Since the polarization was perpendicular to the collimator magnetic field, M_1, the neutral hyperon spin precessed through a large angle (about 150° at full field) between the target and the decay vertex in the vacuum downstream of the veto counter V. The precession angle was used to extract the Λ^0 magnetic moment from these data and is presented elsewhere.[5] The polarization at the production target was calculated from the detected polarization, now in the x-z plane, and the precession angle. Some data were also taken with the collimator field off to measure directly the polarization vector at production.

The charged products from the decays $\Lambda^0 \to p\pi^-$ and $\overline{\Lambda}^0 \to \bar{p}\pi^+$ were detected by six multiwire proportional chambers (Fig. 1). Each chamber had two perpendicular signal planes. The spectrometer magnet, M_2, was used to measure the charged-particle momenta. Its field was reversed periodically so that the decay products from equal-momentum Λ^0's and $\bar{\Lambda}^0$'s populated the same regions of the downstream detectors.

The measured momenta allowed both the mass and momentum of the neutral parent particle to be calculated. The mass was computed under each of three hypotheses: $\Lambda^0 \to p\pi^-$, $\bar{\Lambda}^0 \to \bar{p}\pi^+$, and $K_s^0 \to \pi^+\pi^-$. All events which were within three standard deviations of the Λ^0 mass were called Λ^0's since the background from misidentified K_s^0 was less than 1%. Only events which fit the $\bar{\Lambda}^0$ hypothesis but not the K_s^0 hypothesis were retained at $\bar{\Lambda}^0$'s to eliminate the K_s^0 background. This cut removed 20% of the $\bar{\Lambda}^0$ sample. The hyperon polarization, $\vec{P}$, was determined from the asymmetries in the distributions of the decay products of the parent particles. For the ith event identified as a Λ^0 ($\bar{\Lambda}^0$), the direction of the proton (antiproton) in the Λ^0 ($\bar{\Lambda}^0$) center of mass, $\vec{k}_i$, was calculated. The distribution of protons (antiprotons) in the hyperon center of mass is of the form $[1+\alpha(\vec{P}\cdot\hat{u})(\vec{k}_i\cdot\hat{u})]$ for $\hat{u}$ being each of the three coordinate directions $(\hat{x},\hat{y},\hat{z})$. This expression was modified by the acceptance of the apparatus for hyperon decays, and in the $\bar{\Lambda}^0$ sample by the elimination of events which satisfied the K_s^0 mass hypothesis. Modified distributions were fitted to the data to determine $\vec{P}\cdot\hat{u}$ for each of the fixed coordinate axes.[2,6] The measured polarization was in the x-z plane. The Λ^0 parity-nonconserving components at production were always consistent with zero: $P_v = 0.0005 \pm 0.0017$, $P_z = -0.002 \pm 0.002$. It was assumed that the $\bar{\Lambda}^0$ magnetic moment $\mu_{\bar{\Lambda}}$, and decay parameter $\alpha_{\bar{\Lambda}}$, were equal and opposite to those of the Λ^0.

This analysis includes 3×10^6 $\Lambda^0 \to p\pi^-$ and 2.5×10^5 $\bar{\Lambda}^0 \to \bar{p}\pi^+$ decays where half of the hyperons were produced at $+7.2$ mrad and half at -7.2 mrad. Figure 2 shows the measured Λ^0 polarization versus laboratory momentum plotted separately for $+7.2$ and -7.2 mrad. It is clear that the polarization reverses its direction in space. These data were combined by taking one-half their difference for each momentum bin. The results are given in Table I as a function of x and p_T. The values of p_T and x are correlated through the fixed production angle. In addition 5.3×10^5 Λ^0 and 6.5×10^3 $\bar{\Lambda}^0$ decays were obtained at a production angle of 0 mrad where parity conservation and rotational invariance allow no polarization. None was observed: $P_\Lambda = 0.006 \pm 0.004$ and $P_{\bar{\Lambda}} = -0.011 \pm 0.034$.

The Λ^0 polarization data, together with the 300-GeV results,[1] are shown in Fig. 3(a). The 300-GeV data combined several production angles and each point was summed over x. The average x for each point is given in the figure. The comparison between 300- and 400-GeV data shows no obvious x dependence of the polarization.

This experiment has extended the Λ^0 polarization measurement to a transverse momentum of 2.1 GeV/c from the previous maximum of 1.6 GeV/c. The Λ^0 polarization is perpendicular to the production plane as required by parity and is negative falling monotonically with increasing p_T. There is some indication that the slope may be decreasing above $p_T = 1.6$ GeV/c. This polarization appears to be energy independent between 24 and 400 GeV.

The polarization of $\bar{\Lambda}^0$'s is given in Fig. 3(b) and the table. The data show that $P_{\bar{\Lambda}}$ is consistent with zero up to $p_T = 1.2$ GeV/c. The χ^2 per degree of freedom for this hypothesis is 0.6. The hypotheses that $P_{\bar{\Lambda}} = P_\Lambda$ for 0.37 GeV/$c \le p_T \le 1.16$ GeV/c has a χ^2 per degree of freedom of

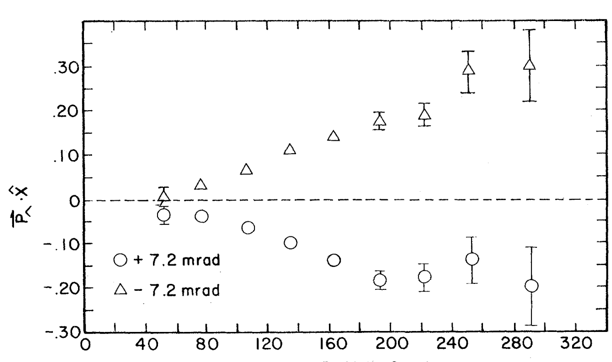

FIG. 2. Λ^0 polarization vs Λ^0 momentum for production angles of $+7.2$ and -7.2 mrad. The direction of the polarization is positive in the direction of $+\hat{x}$.

TABLE I. Λ^0 and $\bar{\Lambda}^0$ polarization for 7.2-mrad proton production as a function of hyperon transverse momentum p_T, in GeV/c, and Feynman x.

$\bar{p}_T$	$\bar{x}$	P_{Λ^0}	$P_{\bar{\Lambda}^0}$
0.37	0.11	-0.022 ± 0.011	-0.02 ± 0.02
0.54	0.18	-0.034 ± 0.003	-0.00 ± 0.01
0.74	0.25	-0.070 ± 0.003	0.01 ± 0.01
0.95	0.32	-0.104 ± 0.003	0.01 ± 0.02
1.16	0.39	-0.139 ± 0.005	-0.02 ± 0.04
1.38	0.48	-0.181 ± 0.008	0.00 ± 0.20
1.60	0.56	-0.209 ± 0.014	
1.81	0.63	-0.223 ± 0.026	
2.09	0.72	-0.237 ± 0.044	

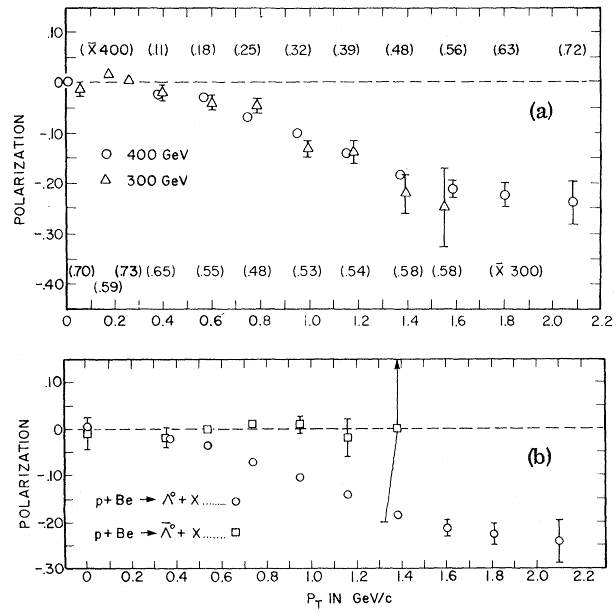

FIG. 3. (a) Λ^0 polarization from this experiment compared to that from 300-GeV incident protons from Ref. 1 as a function of p_T. The number in parentheses is the average value of x for that point. (b) Λ^0 and $\bar{\Lambda}^0$ polarization from this experiment. The polarization is defined as positive along $\hat{n} = (\vec{k}_p \times \vec{k}_\Lambda)/|\vec{k}_p \times \vec{k}_\Lambda|$.

24 indicating that the two are definitely different.

The above comparison makes it clear that polarization is not a universal property of all high-energy baryon production. Λ's, which in this experiment are leading particles, are polarized while the antilambdas, which are unrelated to the incident particle, are not. From the quark picture outlined previously, it might appear that the s quark of the Λ^0 is produced polarized while the $\bar{s}$ quark of the $\bar{\Lambda}^0$ is not. Figure 4 illustrates a mechanism, gluon bremsstrahlung, which could give rise to a Λ^0 polarization without a $\bar{\Lambda}^0$ polarization. In the interaction two of the proton quarks, u and d, are spectators in a singlet spin state. The other u quark is scattered by the target and radiates a gluon which produces an $s\bar{s}$ pair. It is the s from the pair which gives the Λ^0 both its transverse momentum and its spin. The scattered u quark, the $\bar{s}$, and the fragments of the target form the unobserved products. If the gluon is polarized, so is the $s\bar{s}$ pair and this polarization is correlated with the transverse-momentum direction of the Λ^0. To produce a $\bar{\Lambda}^0$, on the other hand, $\bar{u}$ and $\bar{d}$ quarks must also be produced. Regardless of how they are produced these quarks would contribute to the $\bar{\Lambda}^0$ transverse momentum but not its polarization. Thus

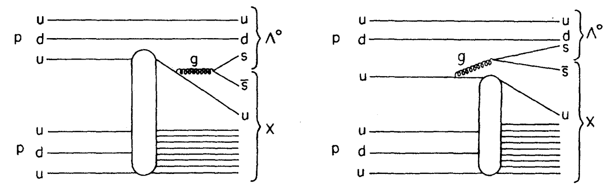

FIG. 4. The gluon bremsstrahlung mechanism discussed in the text.

the $\bar{\Lambda}^0$ polarization at a given p_T would be suppressed.

If a diagram such as Fig. 4 is assumed for other baryon production processes, and if all $q\bar{q}$ pairs are produced with the same polarization, then SU(6) quark wave functions can be used to calculate various baryon polarizations in terms of P_Λ for $p \to \Lambda^0$. The results are $P_p = \frac{2}{5}P_\Lambda$ for $p \to p$, $P_n = \frac{1}{2}P_\Lambda$ for $p \to n$, $P_{\Sigma^0} = -\frac{1}{3}P_\Lambda$ for $p \to \Sigma^0$, and $P_{\Sigma^+} = \frac{1}{3}P_\Lambda$ for $p \to \Sigma^+$.[7] The proton polarization will probably be diluted since the inclusive cross section does not necessarily involve the production of a new proton valence quark. All these predictions are experimentally testable. It would be of great interest to study polarizations of other high-energy baryons.

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Unified Approach to Jet Processes in Quantum Chromodynamics

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We have analyzed in the leading-logarithm approximation a closed set of equations, the solution of which describes correctly the processes $e^+ + e^- \to$ anything, $e + h \to e$ + anything, and $e^+ + e^- \to h$ + anything. This approach allows us to justify clearly the application of the renormalization group and the so-called factorization property. Since the technique is basically a skeleton expansion, it should be useful to give a unified description of all jet processes.

The discovery of asymptotic freedom[1] has made it meaningful to calculate perturbatively to investigate the short-distance behavior of physical processes. The most celebrated example is in deep-inelastic leptoproduction, wherein one deploys the full machinery of the renormalization group (RG) and operator product expansion (OPE).[2] The latter is necessary in order to isolate the so far uncalculable long-distance contribution, related to the composite nature of a hadron with the attendant color confinement effects.

There is yet another way to look at high-energy processes in a renormalizable theory. This is to arrange an approximation in such a way that unitarity is enforced to the desired order. It is quite persuasive that the same RG and OPE results can be reproduced.[3] This route, though tedious at times, offers some advantages. Technically, because of its implementation, one does not have to be mired in the deep Euclidean region, which is the proper domain of RG and OPE. Thus, many more physically interesting processes can be investigated. It is physically direct, since one now works with variables which make closer contact with the processes involved and some quantities, such as "anomalous dimensions," are more ready for interpretation.[4,5] We may call this a procedure to unfold the physical content of the RG.

We have launched a program in this direction and this note is a brief summary of our general attitude and procedure and of some results obtained. Briefly speaking, we have succeeded in developing a closed set of equations via skeleton expansion, such that their solution agrees with the results via RG (and OPE) in areas where such a method is applicable. The technique is general enough that it can be applied to jet processes in all kinematically justifiable regions.

Specifically, let us consider the following three processes: (i) $\gamma(q) \to$ anything; (ii) $\gamma(q) \to a(p)$ + anything; and (iii) $\gamma(q) + a(p) \to$ anything, where γ is assumed to couple to a conserved current. $a(p)$ is a hadron of momentum p. In our approach, all these processes are studied simultaneously.

We have investigated this problem in $(\varphi^3)_6$ and quantum chromodynamics (QCD), both of which are asymptotically free. Since the method is much more transparent in $(\varphi^3)_6$, we will begin with it to introduce the subject matter. The essential arguments carry through in QCD and we will indicate the refinements later.

Except for some inessential kinematics, all three processes are embodied in the study of two structure functions of jets. Let $F(k^2)$ be the total probability for a virtual jet φ of squared invariant mass k^2 to decay into anything, and $F(k,p)$ be the probability to find one hadron of momentum p in this jet.

If radiative effects are temporarily set aside, then at the tree level, the diagonal terms give the leading logarithmic contribution as $k^2 \to \infty$ in all orders of the coupling constant g.[6] As emphasized earlier, however, a high-energy approximation makes sense only if unitarity is respected to that same level of accuracy. Unitarity is easily restored here, if one notices that a jet is actually the imaginary part of the φ propagator. Note further that when a cut is made to a self-energy diagram to obtain the corresponding